The Application of Risk Management to the NEO Threat

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In the spring of 1995, the author, as Adjunct Professor of Engineering at the University of Southern Cal ifornia, developed a new graduate level course in risk management applied to problems in systems engineering and program management. The class project for this course was the near-earth-object (NEO) threat. Twelve graduate students --many with at least a decade of industrial experience -- received final credit towards their MS or PhD programs. Systems engineering has been converging to a more formal discipline over the last several years, but risk management has been one of the most recent arrivals to be recognized within this relatively new field. If risk management is performed at all, it is usually ad hoc and qualitative. The core of this new course established risk management on the foundation of probabilistic decision theory. For the class project, the students were asked to develop decision networks, probability assessments, and alternative criteria relating to the conduct of a planetary defense program. A remarkably good consensus was obtained: all investments for acceleration of NEO detection and characterization as well as preliminary design of mitigation systems were shown to be very cost effective, key risk reduction tests on mitigation technologies were recommended within limits, and the full deployment of actual mitigation systems should be paced by the results of the NEO detection program.

Introduction

Virtually every identifiable trend is driving humanity's enterprises into more intimate interaction and conflict. Increased population, accelerated exploitation of resources, and transportation have brought the previously decoupled worlds of economics, energy and the environment into a tight zero sum game. With the greater efficiency of travel and communication, the emergence of global marketplaces and the revolution in military strategies, the international world is incredibly more interactive, multidimensional and complex than even a decade ago. All of these issues have been aggravated by an explosion of new technology and -- especially in the United States -- a compulsion to force these new technologies into early and simultaneous application. Humanity's challenge is either to manage this complexity or the complexity will manage us, and we will be overwhelmed by ineffective, costly and late systems which are unbalanced, incomplete, incoherent, irrational, divergent, polluting, and generating unnecessary risk at every turn.

Responding to this need, the University of Southern California (USC) has embarked upon an academic strategy which will develop the theoretical and practical foundation to manage complex systems. New courses in systems engineering, management of technology and interdisciplinary studies are being established. Having just retired after four decades in the aerospace industry and having been one of the founders of the National Council on Systems

Engineering (NCOSE), the author was invited to initiate a new graduate course in risk management within systems engineering. This course was designated ISE 599 and was given for the first time in the spring of 1995. The twelve graduate students who received credit for this course were unusual in that the majority were working full time and had at least a decade of experience in the development and analysis of complex systems. Most were in the aerospace industry, working for Rockwell, Northrop Grumman, the Aerospace Corporation, or were junior officers in the US Air Force, working for an advanced degree.

Risk Management within Systems Engineering

Even within such a young organization such as NCOSE (only five years old), risk management is a relative newcomer; many argued that it was more appropriately included within program management than systems engineering. Prior to the eighties, risk management was primarily practiced in the business and insurance worlds and was generally unknown as a formal engineering discipline. When risk management first began to be used, it was almost entirely on a qualitative basis: likelihoods and consequences of adverse events were characterized as "high, medium, or low" rather than by quantitative probabilities or negative financial impacts. The technique was frequently used to convince a program office that the management reserve should be used to mitigate a problem which was not identified at the program start. Often, only risk analysis was accomplished, without the follow-through of developing a coherent risk mitigation plan which was fully recognized and managed by the program office. Worse yet, there are many recorded incidents of engineers being punished, not rewarded, by identifying new risks in mid-program.

The premise of the new ISE 599 course was that engineering risk management should be quantitative whenever possible and based on the rigorous foundation of modern decision theory. The primary references for the course were: Baird, B., *Managerial Decisions Under Uncertainty,* (Wiley, 1989) and Raiffa, H., *Decision Analysis,* (Random House, 1968), plus about a dozen more references in specific risk domains.

The core of the decision theory methodology covered in these references involves the rigorous use of tree-like decision networks which are comprised of two types of junctions: *action* forks and *event* forks. At the action forks, the decision maker chooses from a finite set of possible actions; at the event forks, a discrete set of possible events -- each with its specific likelihood -- is identified. The action forks must recognize all reasonable decisions available to the decision maker and the sum of all the likelihoods emanating from each event fork must be unity. Where appropriate, costs are associated with actions and payoffs (or penalties) are associated with the probabilistic events. A value function is defined -- usually the Expected Monetary Value (EMV) -- as the optimization criterion and the "best strategy" is defined as that sequence of decisions -- coupled by the set of probabilistic events -- which maximizes EMV. For risk management problems, EMV can be negative. The methodology encourages the insertion of early tests to minimize uncertainty regarding later events which may have very expensive consequences.

Although the decision network clearly shows the exact sequence of decisions, it is usually assumed that the time interval between events is so short that the value of money is constant. Perhaps the most controversial aspect of modern decision theory is that -- in contrast to classical statistical theory -- probabilistic *assessments* are employed in situations where a detailed empirical data base is not available. This is termed the subjectivist approach, or the "Bayesian" approach, (after Thomas Bayes), wherein carefully considered estimates optimally mixed with new data develop "best estimates" to quantify the likelihoods of the events which are the result of decisions.

In summary, modern decision theory depends on three rather distinct cognitive functions: the establishment of a logical network of decisions and events, the assignment of probabilities to the uncertain events, and the choice of optimization criteria. Once these three areas are agreed upon, decision theory's greatest strength is that the optimum decisions or strategies can be derived with mathematical rigor. The author has been in many situations in his career where the basic elements have attained a reasonable level of agreement but the decision process was ad hoc, subdimensional and driven by prior biases. Decision theory provides a rational basis for the collection of data and for attaining a consensus from a diversity of viewpoints.

Although this methodology has proven to be an effective decision tool for a great variety of situations, its simplifications should be clearly recognized: Some problems may involve more complex decision structures than trees, or require continuous probability distributions rather than discrete probabilities, and for many problems with several years between the decision junctions the time value of money (interest, inflation, etc.,) cannot be neglected.

The Near-Earth-Object (NEO)Class Project

The class project for the ISE 599 course in risk management was the evaluation of the NEO threat from the standpoint of its credibility, likelihood, consequences, criteria, and optimum pace of managerial decisions and investments. The inputs to the students consisted of *Project Icarus,* (MIT Press, 1968), the reports on *NASA's Detection and Interception Workshops*, the *Congressional Record* covering the hearings on the Asteroid Threat (GPO, March 24, 1993), the AIAA 1990 and 1995 position papers on the NEO, and a series of five lectures on systems aspects of the NEO threat that the author presented as part of MIT's Independent Activities Program in January 1995.

The class project work package, with supplementary data is appended in its entirety at the end of this paper. Twelve questions were asked covering a wide variety of issues related to the NEO threat as well as a diversity of requested responses ranging from mathematically rigorous to purely judgmental. The students were asked to respond from the perspectives of various roles: The head of the International Planetary Defense Agency, the Chair of the Congressional Committee on Science and Technology, the visionary leader of an activist organization, and a graduate student in the management of technology. Also provided were a "starter list" on alternative optimization criteria, monetary values of detection and mitigation systems costs and effectiveness as a function of the time-to-go from detection to impact. *(Note that these cost and effectiveness data are notional only and intended to be merely inputs into an examination on decision theory methodology. The data are smoothed simplifications of values found in the literature and they should not be presumed to be the result of new analysis.)*

The consensus of the students on the qualitative questions was that, without more spectacular "wake-up calls," or substantially more education, the public support for a new NEO program is insufficient to overcome existing priorities, that developing sanctuaries for humanity's survival would be a failed strategy, that international planetary defense is a proper role for the governments of all the developed nations to support, that nuclear contamination of the atmosphere for the purpose of planetary defense would be considered no more justifiable than contamination for military development and that creating a "stunt" involving a false threat is really a terrible idea.

Quantitatively, the students generally agreed that the collection of more threat data was in the fundamental spirit of decision theory, that the perceived threat is reduced as the catalog of NEOs is made more complete and that the value of long range radars -- even at a cost of billions of dollars -- would be a good investment in rapid orbit determination, especially during the terminal trajectory of a long period comet.

The central problem was number nine, which asked the students to develop a "best strategy" for detection and interception system investment against a threat of a 1km asteroid impact which destroys civilization and kills half the human race. A spectrum of investment alternatives, ranging from "continue as-is" to "full development and deployment of both detection and mitigation systems" was to be considered, each with it particular costs and effectivenesses. The primary criterion chosen was to minimize the expected value of rebuilding civilization. A remarkably coherent consensus among the students was attained using the decision theory tools learned during the term:

All investments for the acceleration of NEO detection and characterization, as well as preliminary design of mitigation systems were shown to be very cost effective. Key risk reduction tests on mitigation technologies were valuable for interception development but not deployment. Full development of actual mitigation systems should be paced by the results of the NEO detection and characterization program and coordinated by a central office. The cost to rebuild civilization was given to be one quadrillion dollars, but the conclusions were not very sensitive to this assumption.

Conclusions

The first-order decision theory tools applied to the NEO threat developed a good consensus and derived an optimum strategy on a rational, easily verified basis. However, in order to go more deeply into the details of decisions regarding NEO detection and interception investments, it is recommended that the standard methodology be extended to cover the weaknesses mentioned earlier: permit non-tree decision structures so that investments made today could increase options in the future, permit continuous in addition to discrete probability distributions to capture more accurately the likelihood of future NEO events, and recognize that the very long periods of time between key events and decisions have crucial inflation implications.

CLASS PROJECT ON NEAR-EARTH-OBJECTS

To: Students of ISE 500, "Risk Management within Systems Engineering"
From: George Friedman, Adjunct Professor of Engineering, University of Southern California

Here is your class project. Your response is due 6PM, May 8, 1995. A few comments may be in order.

Many of the problems are analytic exercises which have a unique quantitative answer. Many others, however, are more qualitative and judgmental -- on these there will be no absolutely correct answer. I'm interested in your opinion as an informed, technically educated citizen; please don't give me an answer you believe *I* might prefer. Of course, I'd like you to back up your assumptions and opinions with good discussion.

In the "Spectra, Part I", four personalities associated with the NEO world are described. They may have different viewpoints, depending on their jobs. Help them think through the answers to the questions as if you yourself had the defined responsibilities. It would be advisable for you to read all the spectra before you start answering questions.

Good luck!

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George Friedman

CLASS PROJECT ON NEOs; RISK MANAGEMENT

1) Person C: You have been involved in many crusades in your career and can take pride in the fact that some of today's legislated environmental regulations are due to your efforts. Now, relatively suddenly, you are becoming aware of a new potential threat to humanity: an NEO impact. How do you place this threat within the list of more familiar threats? Why don't you think Walter Karplus included it in the eight risks he discusses in his book, "The Heavens are Falling"?

2) Person C: As you delve more deeply into NEOs, you become intrigued with the concept of developing survival sanctuaries as an alternative to saving humanity from an NEO strike. These sanctuaries could be on earth, on planetary surfaces, or in asteroids or space habitats. Their population should be on the order of a thousand to preserve humanity's genetic heritage and on the order of millions to preserve humanity's cultural heritage. In order to provide an overall balanced perspective, you define these probabilities with respect to some future time, t:
P_1 = probability that humanity will survive
P_2 = probability that a globally destructive NEO will strike the earth
P_3 = probability that humanity will develop an effective NEO defense system
P_4 = probability that at least one human sanctuary will be developed
Derive the logical statement which relates P_1 as a function of P_2, P_3 and P_4.

3) Person C: Is the concept of human sanctuaries morally and practically viable? Even if a few million can survive, why would over 99.9% of the population willingly perish? How would the survivors be chosen? How would they defend themselves and their food supplies from the overwhelming hungry masses? What about the true costs of the sanctuary -- taking into account the required security forces -- relative to the costs of a planetary defense system?

4) Person A: You have just read the 3/24/93 Congressional Record and accept the astronomers' judgmental estimate that the *average rate* of globally destructive NEO impacts on earth is once per million years. Given this assumption of low unit probability and average rate, what type of probability distribution does this suggest? Based on this distribution, what is the probability that there will be an impact this century? In the next 50,000 years? In the next million years? In the next 5 million years?

5) Person A: Fig. 2-5 on p129 of the 3/24/95 Congressional Record compactly relates NEO size, impact energy, chance per year and expected fatalities per event. Is this a cumulative or a probability density function? According to this figure, what diameter NEO is associated with the largest fatality rate? What assumptions had to be made in order to establish such a simple relationship between NEO size and megatons of impact energy?

6) Person A: By analysis of a wide variety of data, the astronomers estimate that there are 2000 NEOs which have the potential of being globally destructive (end of civilization, billions of casualties, and possibly the extinction of mankind). From the interview of David Morrison by

Congressman Ralph Hall (page 177, Cong. Record), how would you assess the quality of the data and the standard deviation about the estimated mean? If 2000 is correct, we have presently catalogued only about 6% of the globally destructive NEOs. It is further estimated that 75% of these NEOs are ECAs and SPCs (with orbital periods on the order of a few years) and 25% are LPCs with orbital periods which can range from thousands to even millions of years.) The Spacewatch program is designed to accelerate the discovery of ECAs and SPCs so that we grow from the 6% knowledge level to the 95% level in less than two decades instead of in two centuries as we would at our present pace. Assume that the Spacewatch program is approved and during its first decade a thousand new NEOs were discovered -- with no NEO detected which would come close to earth within the next 100 years. Could it be said that Spacewatch was therefore a waste? Given this new information, would it be likely that we would change our opinion regarding the entire NEO population? Regarding the average rate of NEO impacts? Regarding the likelihood of a short term NEO hit from the still undiscovered population?

7) Person A: Assume this terminal scenario: A 2km NEO is heading toward earth. If the standard deviation (std dev) of its orbital error projected to earth's vicinity is 100 miles, then we would feel fairly comfortable in applying enough momentum to the NEO to move it an earth's radius transversely. That is, it would be highly unlikely that the NEO would miss and our efforts would result in a hit. However, if the std dev were 10,000 miles, the risk would be far more likely that, in deflecting the NEO's orbit transversely by an earth's radius, we would actually convert a miss into a hit! Assuming that the errors are distributed normally, plot the relationship between the probability of inadvertently converting a miss into a hit vs. the orbital std dev and the number of earth radii we are willing to deflect the NEO. Holding this probability to a limit no greater than .01, plot the tradeoff curve between orbit determination error and NEO deflection energy. If the energy to deflect the NEO by an earth radius cost $1B and a long range laser radar costing $200M could reduce the orbital std dev by a factor of 10, would the radar be a good investment? (Note: energy required is proportional to the transverse distance *squared*)

8) Person B: One of your predecessors, George Brown, authorized two workshops -- one for detection and one for intercept. However they had divergent views regarding the size of NEOs which should be considered seriously, the time frame for new technology development and, perhaps most significantly, the detection workshop claiming that work on intercept was postponable while the intercept workshop claiming that we must get started on intercept concepts and key testing as soon as possible. As we look to future activity, how can these efforts be better coordinated? Is systems engineering and risk management really that important? Do you agree with the AIAA position paper that a program office to assure that the systems aspects are emphasized and to manage interagency and international cooperation would be valuable?

9) Person A: Responding to the urging of Person B, you wish to provide a rational basis for the allocation of resources between varying degrees of detection and intercept activities. For this exercise, you decide to examine the threat of the 1km NEO, with an average impact rate of one per million years, resulting in the destruction of civilization and half of the human population. You consider these six near term decisions: a) No additional investment; continue as is with the search for NEOs; b) Fund Spacewatch - the passive terrestrial detection system - only; c) Fund

Spacewatch plus an active space-based detection system only; d) Fund a full intercept system now, without Spacewatch; e) Fund Spacewatch plus a full intercept system; and f) Fund a full detection system as defined in c, plus a full intercept system. For choices a, b and c, if we discover an incoming NEO, we will launch a crash intercept program. Refer to Spectra IV and V for the performance and costs of alternative detection and intercept systems. For criteria, use: maximization of the probability of preventing the impact, minimization of the loss of human life, the cost to rebuild civilization, the investment costs of planetary defense or some rational combinations of these. Refer to Spectrum II for other possible criteria and introduce more variations if you believe they can illuminate the issue. Draw a decision diagram to illustrate these alternatives and probabilities and discuss the relative merits of the alternatives with respect to the several criteria.

10) Person B: The Nation's science and technology budgets are presently supporting a very wide variety of activities that are perceived to be important to our health, welfare, security or other national objective. (See Spectrum VI) Reflecting on prior federal investments in medical electronics, agriculture, aviation and national security where we attained international prominence, what do think is the appropriateness for federal investment in planetary defense? Given that there are now about 200,000 scientists and engineers in the employ of the federal government, how salable would it be to add about another 100 to get started on a long term planetary defense program? Are you concerned that the issue of the NEO threat is so new, so unrelated to any precedent, of such an incomprehensibly low probability and so closely related to science fiction exaggerations that your credibility, political respect and chance for reelection in two years is seriously affected?

11) Person C: You were previously involved in the advocacy to ban atmospheric nuclear tests and nuclear weapons in space. It now appears that it may be necessary to include nuclear warheads as an option in future planetary defense systems because of their factor of millions advantage in energy density over chemical propulsion and intercept techniques. In an extreme case of nuclear intercept, where an incoming NEO is intercepted but some of the radioactive fragments enter the earth's atmosphere, the radiation level may range from 10% to 1000% of that experienced as a result of the nuclear atmospheric tests of the 1950's. Would you consider these levels an acceptable risk in view of the far higher risk of an NEO impact? Or do you think this nuclear risk -- as well as all other nuclear activity -- is so unacceptable that you would work toward the establishment of a truly long term strategy which relies on chemical energy only and establishes massive stores of energy in space which could be used for a great variety of scientific, exploration, exploitation and colonization purposes in addition to planetary defense?

12) Person D: A professor of engineering at a prestigious eastern university suggested that a tactic to gain worldwide attention and support for planetary defense would be to secretly launch an inflatable 2km "dummy asteroid" to the vicinity of Jupiter and then put it into an orbit that clearly would impact the earth within three years. This object is eight times the volume of the one hypothesized in problem 9 and would doubtlessly put the whole world on a crash program to save itself. This "stunt" could probably be accomplished for $50M, he felt. What do you think of the effectiveness of this tactic?

SPECTRA

I PEOPLE

Person A: Head of the International Planetary Defense Agency (IPDA). You report to the U.N. and receive resources from the Space Agencies and Ministries of Defense of the world's developed nations. You were chosen for your objectivity, communication and managerial skills as well as your understanding of the methods of risk management and decision theory. Your initial budget is relatively small ($50M/yr) and your job is to allocate and manage it rationally and, if appropriate, argue for increased/decreased budgets.

Person B: Chair of the U.S. House of Representatives Committee on Science and Technology. Your constituency is the entire population of the United States. You were chosen for your understanding of the coupling between federal investments in Science and Technology and US industrial competitiveness, health and social needs, environmental quality, and space exploitation and possible defense. Your job is to argue for the proper total level of S&T budget and for rational allocations of the budget dedicated to specific goals.

Person C: Visionary Leader of an Activist Organization to Save Humanity and Maximize its Future Quality of Life. You are supported by the private contributions of 500,000 people worldwide. You were chosen for your balanced idealism, practicality and scientific judgment. Your job is to fund key studies and research with the ultimate purpose of advocating governmental legislation and funding of programs you consider essential to humanity's survival and quality of life.

Person D: You, the Graduate Student who may Become Any of the Above.

SPECTRA

II CRITERIA

C1 Minimize cost of saving the human race *absolutely.*
C2 Minimize cost of saving the human race with a probability of X

C3 Maximize the probability of saving the human race *absolutely.*
C4 Maximize the probability of saving the human race using Y% of GWP.

C5 Maximize the expectation of lives saved per dollar invested (FAA).
C6 Save any life at any cost.
C7 If the risk is nonzero, drive the risk to zero at any cost.

C8 Minimize the regret that humanity will suffer (temporarily) if it learns it will perish and could have survived if it had invested an affordable amount (such as half the consumption of tobacco, alcohol and drugs).

III MONETARY VALUES

M1	Planetary Defense Management Office:	$2M/yr
M2	Continue Present NEO Search Programs:	$3M/yr
M3	Invest in Spacewatch (passive) hardware:	$50M
M4	Develop and Deploy a "Decoy" Asteroid:	$50M
M5	Operate and analyze Spacewatch System:	$10M/yr
M6	NEO Exploration and Characterization Program	$100M/yr
M7	Human Sanctuary on Earth:	$100B
M8	Human Sanctuary on Asteroids and Space Habitats:	$1T
M9	Human Sanctuary on Mars and the Moon:	$10T
M10	Preparing for and waging war:	$1T/yr
M11	Gross World Product (GWP):	$20T/yr
M12	Rebuilding a destroyed civilzation:	$1Q
M13	The irreversible loss of humanity:	**Uncalculable**

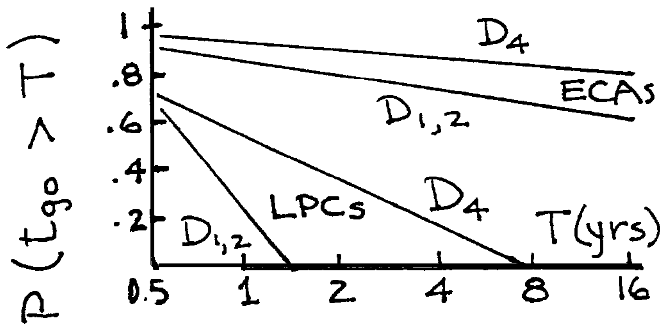
$M = 10^6 $B = 10^9 $T = 10^{12} $Q = 10^{15}

SPECTRA

IV DETECTION SYSTEMS:

D1 Continue as-is; in 200 yrs we'll catalog 75% of NEOs (95% of ECAs)
D2 Spacewatch; passive ground-based; accelerate above by factor of ten
D3 Spacewatch plus long range ground radar; more rapid p(hit) prediction
D4 Spacewatch plus space-based active sensors; 95% of NEOs in 30 yrs

PERFORMANCE



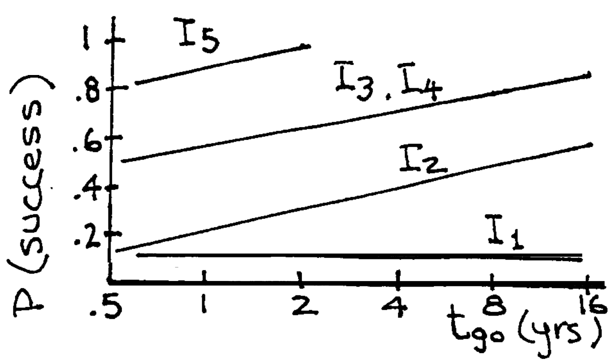
SCHEDULES AND COSTS

D1 \$0 Development, \$5M/yr Ops
D2 \$50M, 10 yr development
\$10M/yr operations
D3 \$200M, 10 yr development
\$10M/yr operations
D4 \$10B, 15 yr development
\$50M/yr operations

V INTERCEPT SYSTEMS

I1 Rely on retargeted ICBMs only
I2 Use existing nuclear warheads delivered by a vehicle and guidance system developed on an emergency basis
I3 Redesign warheads based on key tests and rendezvous with NEOs and deliberate optimized vehicle and guidance system development
I4 Development of a chemical intercept system including storing energy in orbit in advance of a threat detection

PERFORMANCE



SCHEDULES AND COSTS

I1 \$0 development, \$50M/yr ops
I2 \$100B, 3 yr development
\$100M/yr operation
I3 \$100B, 10 yr development
\$50M/yr operations
I4 \$50B, 10 yr development
\$1T 30 year lift energy to orbit